19 Data Acquisition Fundamentals

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INTRODUCTION

Over the last several years, the use of computers and microprocessor-based equipment to measure, control, and test processes and equipment have become the norm, including process, manufacturing industries, and automation. One particular area that has been revolutionized by the rapid technological evolution of the PC is the data acquisition (DAQ), commonly also referred to as DAQ. Today, PC-based DAQ systems are able to tackle a much wider and broader range of applications as predicted by Moore's Law on the continual increase in performance-to-price ratio of PC technologies. This chapter reviews the fundamental concepts of DAQ both from hardware and software technologies' point of view.

DAQ is defined as the general process by which phenomena from the real world is captured and recorded in digital format. The basic elements of a computer-based DAQ system are shown in Figure 19.1. The majority of process equipment, such as sensors and transducers and final control elements, are analog devices and they generate or operate on analog electrical signals. Generally speaking, DAQ hardware performs the conversion from analog-to-digital signals, and vice versa. More often than not, the DAQ device works in conjunction with a computer, such as the standard PC. The computer in this figure runs DAQ software that processes and records the data.

The DAQ devices can take many different forms and implementations. Most of these devices not only incorporate analog input capabilities, but also include provisions for generating analog outputs, digital inputs and outputs, and various counting and timing functions. Figure 19.2, for example, shows a simplified block diagram of a typical multifunction device commercially available from several vendors. It includes one or more analog-to-digital converters (A/Ds or ADC) with accompanying signal conditioning, one or more digital-to-analog converters (D/As or DAC), digital input/output circuitry, and a timing controller.

This chapter begins by explaining the basic concepts of A/D and D/A conversion and the circuits used to carry them out. Also, in addition to A/D and D/A conversions, other indispensable operations, such as signal conditioning and timing controllers, as well as the extremely important software, are required components of an effective DAQ system.

A/D AND D/A SIGNAL CONVERTERS

At the heart of the DAQ system is data conversion, the process of converting analog signals into digital formats, and vice versa. The conversion is carried out in two steps: first the signal is quantified and later it is codified. *Quantifying* means representing the continuous values of the analog signal using a set of discrete values, and *codifying* means representing these discrete values by bit sequences. The number of bits of these sequences determines the number of possible values of the conversion: 2^n for n bits. As an example, Figure 19.3 illustrates the digitization of a 10 V waveform with 3 bits of resolutions.

A/D and D/A provide the interface between the analog world (the real world) and the world of digital computation and data processing. Many of the applications for analog–digital interfaces are quite evident as we use them in our daily lives. Temperature controllers, computers and related peripherals, electronic fuel injection, and compact disc music systems are just a sample of the typical applications that require analog–digital interfaces.

The electronic circuit of A/D carries out the quantification and codification processes. The A/D operates with signals of determined amplitude, for example, between −SV and +SV. Another electronic circuit of D/A carries out the conversion from digital signals into analog signals. This device converts digital codes of n bits into a signal of 2^n discrete levels of voltage or current. We will look at D/A first as they are typically simpler than A/Ds and are often utilized as a component within an A/D.

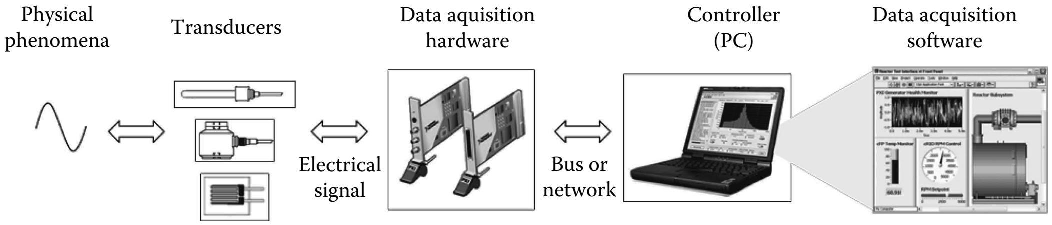

FIG. 19.1
Basic elements of a DAQ system.

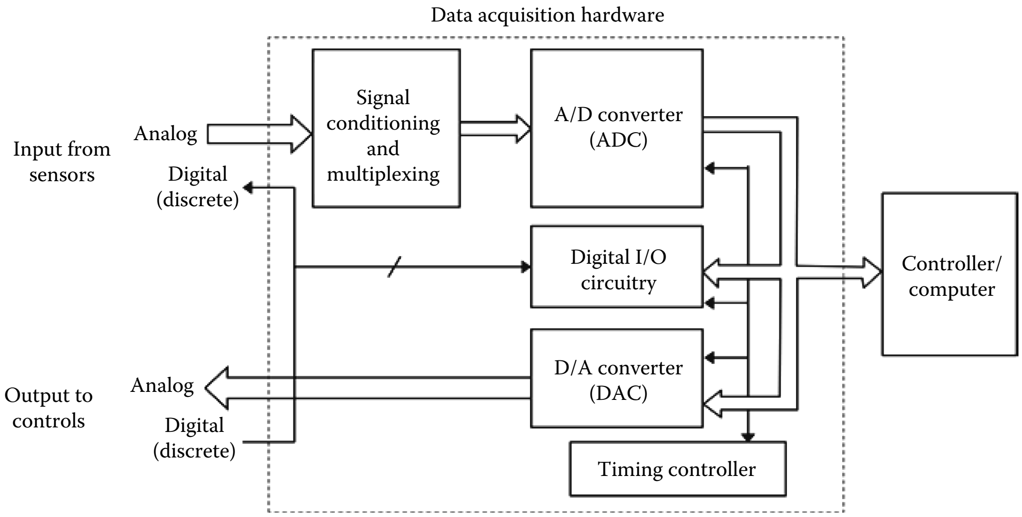

FIG. 19.2
Block diagram of multifunction DAQ device.

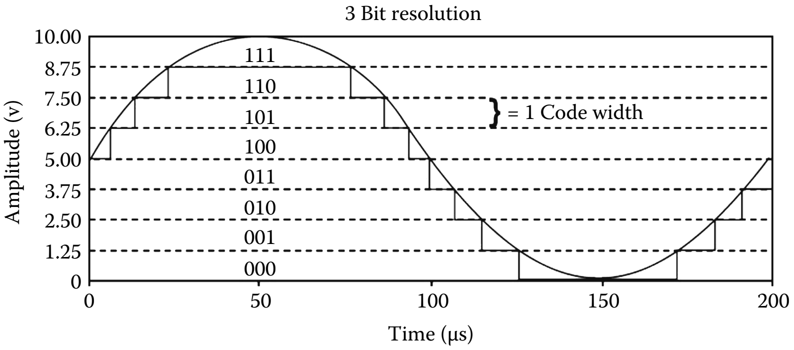

FIG. 19.3
Quantization of analog waveform with 3 and 16 bit converter.

Digital-to-Analog Converters

A D/A is an integrated circuit (IC) device, which converts an *n*-bit digital word to an equivalent analog voltage. DAQ systems often include D/As in order to generate analog signals for control, reference signals, stimulus signals, and so on. Most D/As utilize some combination of a resistive or capacitive network, a switching network, and a summing amplifier.

For example, Figure 19.4 shows a typical design of a simple *n*-bit D/A, referred to as an R-2R ladder D/A. The set of latches holds the binary number, which is to be converted to an analog voltage signal. The output of each latch controls a transistor switch, which is associated with a determined resistor in the resistor network. The voltage reference, which is connected to the resistor network, controls the range of the output voltage. The operational amplifier works as an adder circuit.

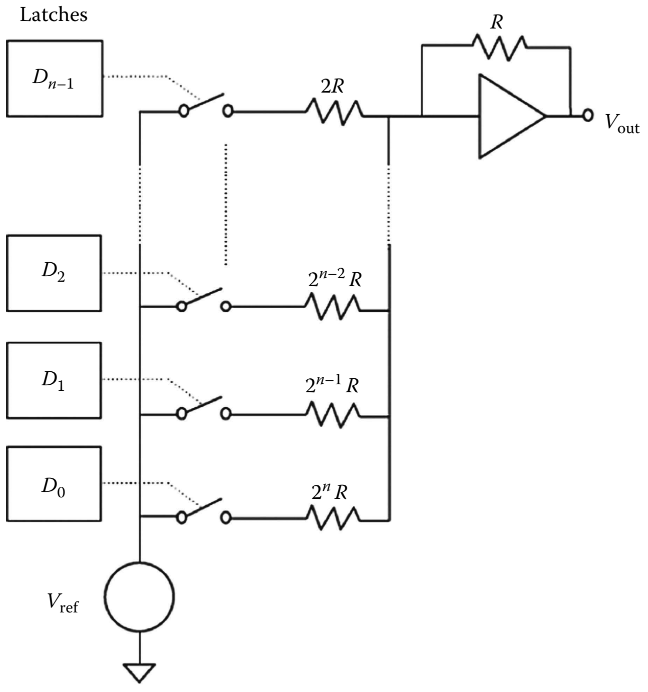

FIG. 19.4
Basic D/A design.

The operation of the D/A converter is as follows:

1. Switches set the digital word, that is, switch is closed for logic ONE and switch is grounded for logic ZERO.
2. The weighted resistors determine the amount of voltage V_{out} at the output.

For each one of the resistors in the network, when its corresponding switch is on, the operational amplifier adds a voltage to V_{out}, which is inversely proportional to the value of the resistor and directly proportional to the reference voltage and the feedback resistor (R). For example, for the $2R$ resistor the operational amplifier adds value to V_{out} as expressed in the following equation:

$$V_{out} = V_{ref}\frac{R}{2R} = \frac{V_{ref}}{2} \qquad \textbf{(19.1)}$$

The total value of V_{out} can be calculated by using the equation

$$V_{out} = V_{ref}\left(\frac{D_{n-1}}{2} + \frac{D_{n-2}}{4} + \cdots + \frac{D_1}{2^{n-1}} + \frac{D_0}{2^n}\right) \qquad \textbf{(19.2)}$$

where D_{n-1}, D_{n-2}, etc., represent the values of the bits of the binary number to be converted.

In this formula, each active bit contributes to V_{out} with a value proportional to its weight in the binary number, and thus the output voltage generated by the D/A is proportional to the value of the input binary number.

Because it is generally easier to sum currents using analog circuitry, many D/As utilize current sources, rather than a voltage reference, and generate a current output that is the weighted summation of currents.

D/A Characteristics

While there are many important specifications that characterize the performance of a D/A, the following are a few key parameters to consider:

Range: The output range of the D/A is the span of voltages, or currents, over which the D/A can generate an output. For example, typical ranges for a voltage output D/A are 0–5, 0–10, ±5, and ±10 V.

Resolution: This is the number of bits used in the digital coding of the value to be converted to an analog signal. The resolution determines the dynamic range of the output signal. For example, a 12 bit D/A can generate a total of $2^n = 2^{12} = 4096$ unique output values. If a 12 bit D/A is configured with an output range of 0–5 V, then the D/A can generate a change in voltage output as small as 5 V ÷ 4096 = 1.22 mV. Most commercial DAQ products today utilize D/As with 8, 12, or 16 bits of resolution.

Settling time: Settling time determines how rapidly a D/A can change its output signal to a new value when the digital input changes, as shown in Figure 19.5. Most D/As specify settling time as a full-scale change in voltage, from the smallest output value to the largest. A D/A with a small settling time can generate high-frequency signals because an accurate voltage level can be obtained in a very small time.

Linearity: Linearity specifies the maximum deviation of the D/A's transfer curve from an ideal straight line, usually expressed as a fraction of the full-scale reading, as shown in Figure 19.5b.

Monotonicity: If a D/A is monotonic, the output always increases with an increase in the digital input. Conversely, a non-monotonic D/A would actually decrease the output at specific code values, and its transfer curve would have a dip.

Analog-to-Digital Converters

A/Ds, of course, perform the reverse operation of D/As, converting analog input signals into a digital, binary representation. The number of bits in this digital representation determines the *resolution*. An A/D with n-bit resolution can generate an output with one of 2^n distinct codes. When combined with the input range, or span, of the A/D, the resolution indicates the smallest change that can be detected in the input signal or the value of one least significant bit (LSB). Table 19.1 compares resolutions commonly available today for some typical input ranges.

There are many types of A/Ds in practical use and the reason for this is that there are a diverse number of applications. Some of the popular A/Ds used in DAQ are as follows:

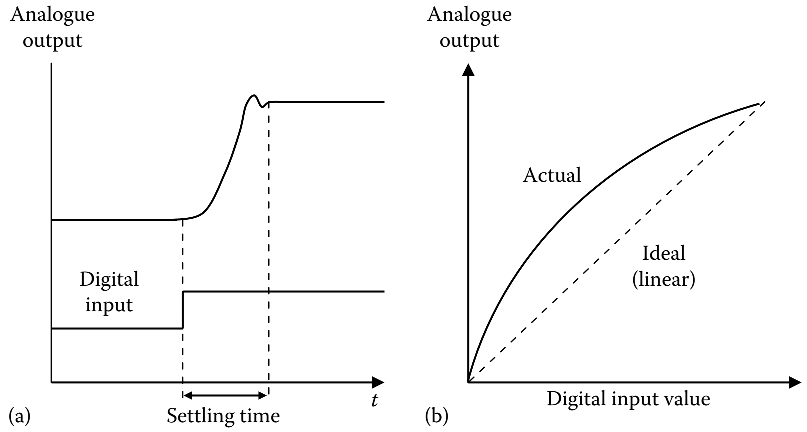

FIG. 19.5
Key D/A characteristics include (a) settling time and (b) linearity.

TABLE 19.1
Comparison of Common A/D Resolutions

	8 bit	*12 bit*	*16 bit*	*18 bit*	*24 bit*
Distinct levels, 2^n	256	4,096	65,536	262,144	16,777,216
Value of 1 LSB for 0–1 V input range	3.92 mV	244 μV	15.3 μV	3.81 μV	0.060 μV
Value of 1 LSB for ±10 V input range	78.4 mV	4.88 mV	305 μV	76.4 μV	1.19 μV
Dynamic range in dB	48.2	72.2	96.3	108.4	144.5

Flash A/D converters (parallel): The fastest type of A/D is the flash or parallel converter, obtaining speeds in multiple gigasamples per second. However, the parallel architecture employed by the flash converters tends to limit practical implements to 10 bits or less of resolution.

An n-bit flash A/D utilizes 2^n reference voltage levels and $2^n - 1$ comparators, as shown in Figure 19.6. The input analog voltage is connected to the input of every comparator so that a comparison can be made with each of the reference voltages representing the quantization levels. The outputs of

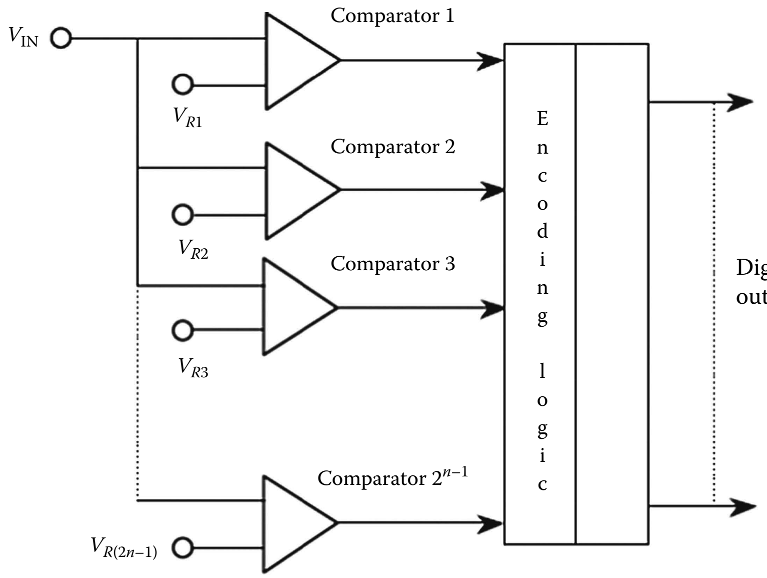

FIG. 19.6
Flash A/D Converter.

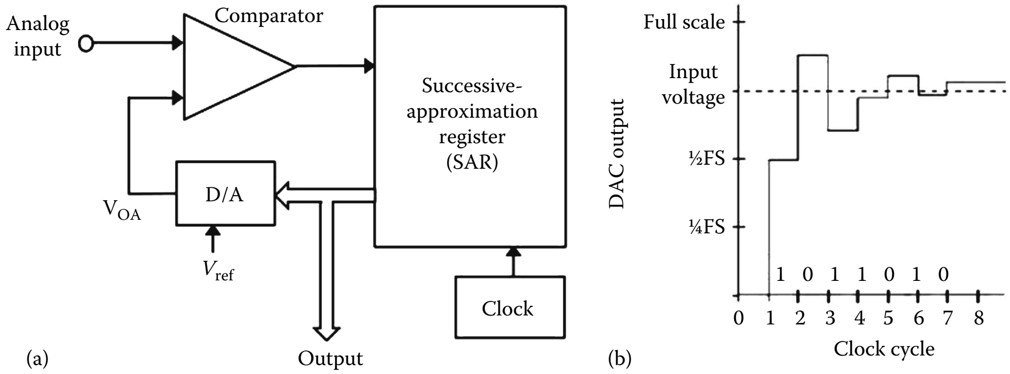

FIG. 19.7
(a) Scheme of a successive approximation A/D. (b) Output bit generation of the process.

the comparators then drive the encoding logic to generate the equivalent digital output.

The conversion rate for flash A/D converters is very fast because only one step is required for complete conversion. The main disadvantage of the flash converter is of course the number of comparators and reference voltages required to implement large-scale converters. For every additional binary bit of resolution added to the converter, the number of comparators required is essentially doubled. For instance, 255 comparators are required for an 8 bit converter. If 4 more bits were added, 4095 comparators are required for a 12 bit converter.

Successive approximation converter: The successive approximation register (SAR) A/D is the most popular architecture for DAQ applications, with many options available covering a wide range of resolution and speed at an affordable cost. Modern SAR A/Ds are available in resolutions of 8–18 bits, with sampling rates up to tens of megasamples per second.

The basic architecture of a successive approximation converter is shown in Figure 19.7. The analog input to this system is successively compared with the voltage generated by a D/A. The digital input to the D/A, which is stored in the SAR is adjusted according to the result of each comparison. If the converter is of *n* bits, the conversion process requires *n* comparisons, and the result of the conversion is the final value stored in the SAR.

The conversion process for this A/D converter is as follows:

1. The most significant bit of the SAR is set to logic ONE, causing the internal D/A output to go to midscale.
2. The output of the decoder is compared against the input analog signal. If the analog signal is larger than the D/A output V_{OA}, then a logic ONE is registered for the most significant bit. If the signal is less than the D/A output, the bit value is replaced with a logic ZERO.
3. The successful approximation register then goes to the next bit and tries logic ONE for that bit, which sets the D/A output to either ¼ scale or ¾ scale, which is compared to the input signal.
4. This process of comparison is repeated for *n* bits until the signal has been converted.

Figure 19.7 also shows an example conversion process of a value of an analog input. Only the calculation of the seven most significant bits of the digital output is shown.

Delta-sigma A/D converter: The delta-sigma, or sigma-delta, converters have become a very important technology for DAQ applications in recent years. Delta-sigma A/Ds commonly provide 24 bits of resolution at sampling rates that now reach up to hundreds of thousands of samples per second. Their combination of speed, high resolution, and inherent anti-aliasing and noise filtering capabilities make the delta-sigma A/D reduce or even eliminate the need for expensive instrumentation amplifiers and other signal preconditioning. As such, delta-sigma converters offer an attractive option for a wide range of applications ranging from low-level sensor measurements to dynamic vibration and audio analysis.

The basic concept of the delta-sigma converter is to greatly oversample the input signal with a 1 bit A/D (essentially a comparator) and then use digital signal processing (DSP) methods to reshape the quantization noise. Figure 19.8 shows a simplified block diagram of a basic single-order delta-sigma converter.

The single-bit modulator is comprised of a subtraction node, a loop filter, a 1 bit A/D, and a 1 bit D/A in a feedback loop. Both A/D and D/A are oversampled at rates much

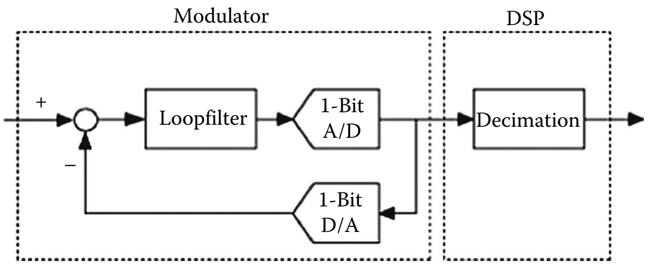

FIG. 19.8
Topology for a simple single-bit sigma-delta A/D.

higher than the desired sampling rate, often at rates 64 or 128 times the eventual sample rate. The modulator section of the A/D generates a bitstream whose average level, thanks to the negative feedback loop, approximating the input signal level. The DSP section of the delta-sigma A/D consists of a low-pass filter, which converts this high data-rate bitstream into a high-resolution signal value.

A/D Characteristics

While resolution and speed of conversion are the fundamental specifications, the following key parameters are particularly important in characterizing the operation and performance of A/Ds.

Input range: The input range of an A/D is the span of voltages over which it can make a conversion. The end points of the low and high end of the range are called −full scale and +full scale (they are also referred to as rails). If the −full scale is equal to 0 V, then the range is referred to as unipolar, and if the two full-scale values have the same magnitude, for example, −5 to +5 V, then the range of the A/D is referred to as bipolar. If an input voltage falls outside the range, the converter is said to be overranged. In this case, most converters will return a value of the end point closest to the sampled signal.

Linear errors: Linear errors, namely, DC offset errors and gain errors, are the largest and most common errors in an A/D. However, they are easily corrected through simple calibration and linear correction.

Nonlinear errors: Nonlinear errors are characterized by two specifications: differential nonlinearity (DNL) and integral nonlinearity (INL). DNL measures any irregularity in the code width (smallest detectable change) by comparing the actual change in value to the ideal value of one code width (or 1 LSB). INL measures the deviation from an ideal transfer line of the code transitions. Unlike linear errors, nonlinear errors are more difficult to compensate for in either the analog or digital signal. The best way to mitigate nonlinear error is to choose a well-designed, well-specified A/D.

Relative accuracy: Another way to express the nonlinearity of the A/D is relative accuracy, which is the worst-case deviation from the ideal DAQ board transfer function, a straight line. A relative accuracy test is run by linearly sweeping the input from minus full scale to plus full scale and comparing the average of the digitized values to the values of an end-point-fit straight line, created from an endpoint fit of the data. Relative accuracy includes all nonlinearity and quantization errors but does not include offset and gain errors of the circuitry feeding the converter. The relative accuracy is measured in LSBs. In practice, a good A/D will have a relative accuracy of less than ±1 LSB. The relative accuracy is a very important specification because it tells how accurately the continuous analog input range is converted to discrete digital values.

DAQ SYSTEMS

While the A/Ds and D/As are core components of the DAQ device or system, there are other critical functions required to make useful measurements or effectively control a process. Most DAQ devices are designed to handle more than one sensor inputs and so incorporate either a *multiplexer* or additional circuitry to simultaneously acquire data from multiple inputs. Interfacing to real-world sensor outputs usually requires some type of *signal-conditioning* circuitry that preconditions the signal, or sensor output, improving the quality and reliability of the measurement. DAQ systems will also require a *system timing controller,* which can generate the needed clock and timing signals to accurately and precisely control the timing of the acquisition.

Additionally, many commercial DAQ products fall into the class of multifunction I/O, meaning they combine analog input functionality with analog output, digital input/output, counter, and timing input/output capabilities. The following sections will examine the different components that comprise a typical DAQ device.

Multiplexers and Multichannel Systems

A DAQ system typically involves multiple sensors or analog inputs, sometimes reaching channel counts in hundreds or even thousands. In order to efficiently and economically address these multiple channel applications, DAQ products tend to employ either a multiplexed architecture or an A/D-per-channel architecture.

A multiplexed DAQ system employs a switching device, called a signal multiplexer, to sequentially connect analog signals to the A/D system, as shown in Figure 19.9. With the multiplexed system, one A/D device can be shared across many analog inputs, yielding a more economical and compact system design. The signal-conditioning circuitry may be located either before or after the multiplexer, depending on the application.

One potential disadvantage of the multiplexed systems is that the acquisition speed is limited to the rate at which the multiplexer can switch, including the time for the analog input signal to settle to the correct value, the rate of the single A/D to sequentially convert the input signals. For example, a system with a 16 channel multiplexer and a 200 kSamples/s (5 µs) converter would take a minimum of 80 µs to convert one sample from each channel, yielding a maximum sampling rate of 12.5 kS/s for each input. Additionally, a time skew, or delay, is present in the scanned data, which is equal to the conversion rate (5 µs in this example). Some devices will employ sample-and-hold amplifiers on each channel to remove this time skew and obtain simultaneous measurements.

Alternatively, a DAQ device can be designed with a more parallel architecture, as shown in Figure 19.10. This type of system uses a distinct A/D, along with any needed signal conditioning, for each input channel. This architecture,

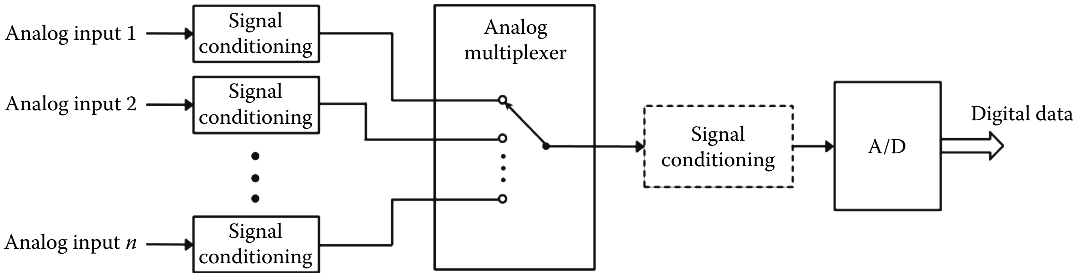

FIG. 19.9
Multiplexed analog inputs.

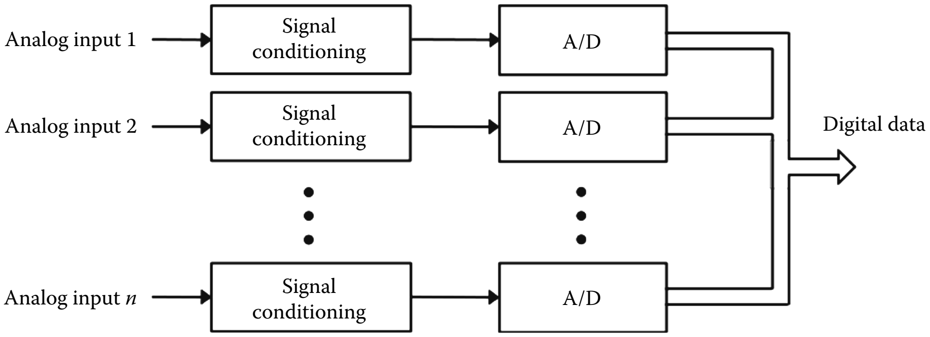

FIG. 19.10
Parallel A/D-per-channel DAQ system.

which avoids the performance bottleneck of the multiplexed architecture and can inherently provide simultaneous digitization of all input channels, is popular on higher speed systems. The disadvantage of the A/D-per-channel architecture is the added cost and space for the additional circuitry.

System Timing Controller

High-speed DAQ applications require that the A/D conversions occur automatically, at very precisely defined time intervals. Therefore, a DAQ device must be equipped with a system timing controller whose principal responsibility is to generate the timing signals that control the synchronized operation of the A/Ds, multiplexers, movement of digital data, as well as analog output D/As, digital I/O, and counter/timer I/O.

Timing controllers include a frequency source, or timebase, for example, a 10 MHz oscillator, and a system of dividers and timing circuitry that can generate the various timing signals required to control the DAQ system. For example, the timing controller may need to be able to generate a 1 s clock signal for slow-speed temperature monitoring or a 1 MHz clock to time high-speed ultrasonic signals.

The system timing controller also typically generates a number of different timing and triggering clock signals. For example, a multiplexed analog input device may require a control signal to initiate a scan of all channels at one time interval (T_{scan}), but also multiplex through the individual input channels at a different rate, referred to as the sample interval (T_s). Additionally, the entire sequence can be initiated with an external trigger signal. An example of a timing diagram of this scenario is shown in Figure 19.11.

Multifunction I/O Systems

As mentioned earlier, a common type of DAQ device is the multifunction I/O DAQ device that combines analog input, analog output, digital input, digital output, and counter/timer inputs and outputs. In modular systems, individual modules may be a single function system but can be mixed and matched to form a multifunction system.

Analog output: Many DAQ devices and systems include two or more analog output channels that utilize D/As to generate analog voltages to generate control signals. Typically, the analog outputs can generate voltages up to 5 or 10 V although some DAQ boards designed for more industrial applications can directly generate a 4–20 mA analog output. By adding a timing controller and buffer memory to hold arrays of digital values to be converted, an analog output device can generate dynamic waveform signals that can be used to simulate signals used as a stimulus or a reference in a test.

Digital I/O: Most DAQ devices include several general-purpose digital inputs and outputs or digital I/O. Digital I/O can be used for a wide variety of applications, including sensing the on/off state switches and other binary sensors, controlling external relays and actuators, generating test patterns, and simple parallel I/O communication. Most digital I/O on

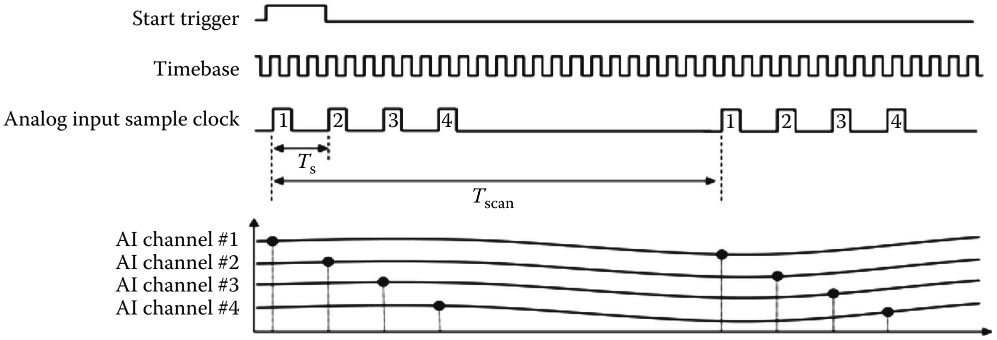

FIG. 19.11
Timing diagram of scanned DAQ sequence.

computer-based DAQ works at 5 V and is transistor-transistor logic (TTL) compatible, which defines the low and high states of the digital signals, as illustrated in Figure 19.12. Alternatively, some digital I/O devices designed for industrial control and monitoring applications may implement digital I/O that operates directly with 24 V sensors and actuators.

Counters/timers: Counters/timers are versatile devices used for a variety of counting, timing, and signal generation applications. Counter/timer functionality is accomplished through the use of one or more counters and one or more frequency clock sources or timebases. The counter itself is a basic device that consists of a count-register, GATE and SOURCE inputs, and an OUT signal (Figure 19.13). The counter's basic operation is to increment the count-register on every detected state changes at the SOURCE INPUT. Counting is controlled, or gated, by the state of the GATE signal. The OUT can be configured to generate a pulse, or a change of state, when the count-register reaches a preprogrammed count value.

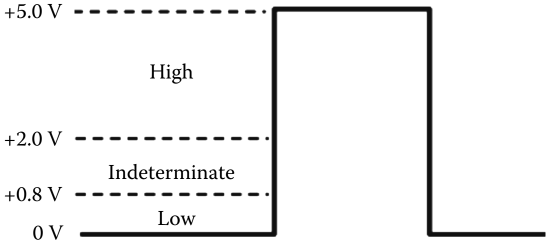

FIG. 19.12
Voltage levels of digital TTL signal.

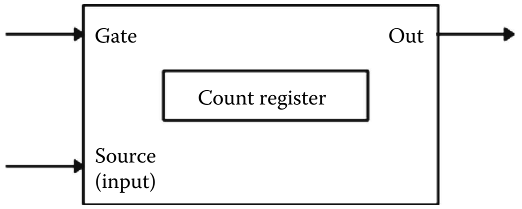

FIG. 19.13
Basic counter device.

By combining one or more counters with a frequency clock source, a counter/timer device can be configured for a wide range of counting and timing operations:

- Event (pulse) counting
- Pulse-width and period measurement
- Pulse-width modulated inputs and outputs
- Frequency measurement
- Frequency generation
- Pulse train generation

SIGNAL CONDITIONING

Most sensors and transducer generate signals that cannot be, or should not be, connected directly to the unconditioned input of an A/D. The sensor signals may be very low and vulnerable to noise corruption or very high and outside the usable range of the A/D or even pose a safety issue. Many popular sensors generate a resistive signal, which must essentially be converted to a measurable voltage signal. A typical signal-conditioning circuitry provides (Figure 19.14) the front-end analog preprocessing required to convert the output from the sensor into conditioned signals, which can be effectively digitized and acquired. Signal-conditioning functions include amplification, filtering, isolation, sensor excitation, and other sensor-specific functions.

In commercial DAQ systems, signal conditioning may be provided as a front-end unit that attaches or cables to the digitizing DAQ device. This modularity allows mixing and matching the signal conditioning to match the application as needed. Alternatively, an approach that is gaining popularity as the size and cost of analog and digital IC technology continues to decrease is to integrate signal-conditioning capabilities into the DAQ device. An advantage to this integrated approach is that the system design can be optimized, both in terms of cost and performance, for more specific applications.

More information on signal conditioning can be found in Chapter 18.

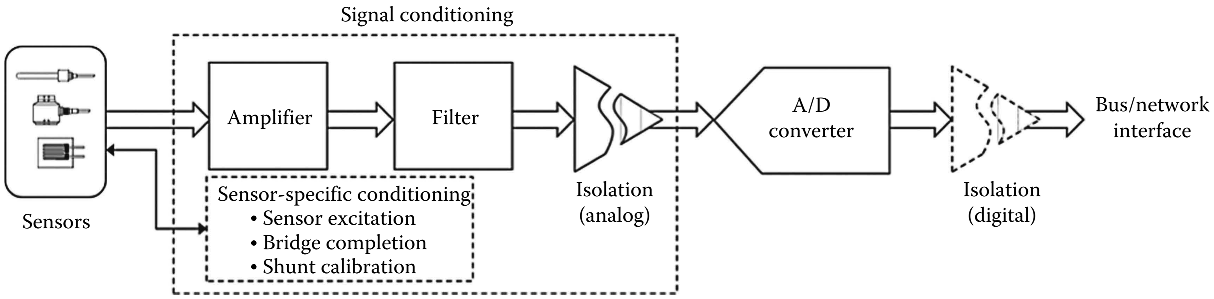

FIG. 19.14
Signal conditioning includes amplification, filtering, isolation, and sensor-specific function for interfacing to popular industrial sensors and transducers.

Amplification

Amplification is the most common signal-conditioning function and is critical in effectively utilizing the resolution of the A/D subsystem. The converter in the DAQ system operates over a fixed input range, with a fixed resolution. For example, as we saw earlier that a 16 bit A/D with a ±10 V input range yields a signal resolution of 305 μV, which would be more than sufficient for voltage signals that operate over the full 10 V input range. However, consider using this same system to digitize a typical thermocouple that generates a signal that varies with temperature at a rate of approximately 50 μV/°C and will never exceed a maximum level of 100 mV. The 16 bit system, with a resolution of 305 μV, can detect changes no smaller than 6°C. However, by adding a low-noise signal amplifier with a gain factor of 100, the resolution of the system is increased to 3.05 μV. With this amplification, temperature changes of less than 0.1°C can be detected (neglecting other sources of error and noise, of course). Note that the effective input range of the DAQ device is also reduced by a factor of 100 to ±200 mV.

Another important function of amplification is to increase the signal-to-noise ratio, reducing the error caused by noise imposed on the signal after being amplified. Noise that is coupled into the measurement signal path will have a proportionately smaller effect if the analog signal has been amplified to a higher level. That is why it is often desirable to amplify the signal as close as possible to the source before the signal is transmitted through a noisy environment.

Filtering

Filtering removes or decreases the unwanted noise from signal measurements. Filters operate as a function of frequency, and can selectively attenuate signals above a certain frequency (low-pass filters), below a certain frequency (high-pass filters), within a frequency range (notch filters), or all frequencies except a specified range (band-pass filters). Low-pass filters are the most common in industrial applications and are used to reduce the effects of higher frequency noise from power lines, generators, motors, etc.

A second important application of filters is to remove errors caused by aliasing. Aliasing is the phenomena whereby high frequency signals show up as low frequency signals because of undersampling. Anti-aliasing filters reduce or remove these aliased signals by implementing high-order low-pass filters that sharply attenuate all signals above one-half of the sampling rate, also known as the Nyquist frequency. As we saw earlier, sigma-delta A/Ds incorporate very effective noise and anti-aliasing filtering as a useful by-product of the digitization scheme. Alternatively, regardless of the type of converter, it is often very effective to oversample a noisy signal at a higher rate and apply basic averaging, or digital filters, in the software application. This approach does not provide true anti-aliasing, but it can reduce other noise and increase the frequency at which aliasing would occur. In any case, many DAQ and signal condition products do incorporate some type of analog filtering to pre-filter the signal in the analog domain, either as a precaution for anti-aliasing or to clean up signals distorted with noise from the environment, such as 50 or 60 Hz noise from power lines. Figure 19.15 illustrates the effect of a low-pass filter on a noisy strain gage signal.

Isolation

One of the most common causes of measurement problems and failures is improper grounding of the signal wires. For example, if a sensor is electrically referenced to a local ground point that is not exactly at the same potential as the ground of the DAQ system, the difference in potential can show up as an offset error or noise in the measurement. If the ground potentials are far enough apart, they can cause damage to the DAQ equipment. Signal conditioners with isolation can prevent most of these problems. Such devices pass the signal from its source to the measurement device without a galvanic or physical connection, breaking the path for currents to flow between grounds at differing potentials. Besides breaking ground loops, isolation blocks high-voltage surges and rejects high common-mode voltage and thus protects both the operators and expensive measurement equipment.

Isolation of analog signals is usually implemented using capacitive or magnetic isolation techniques. Optical isolation is

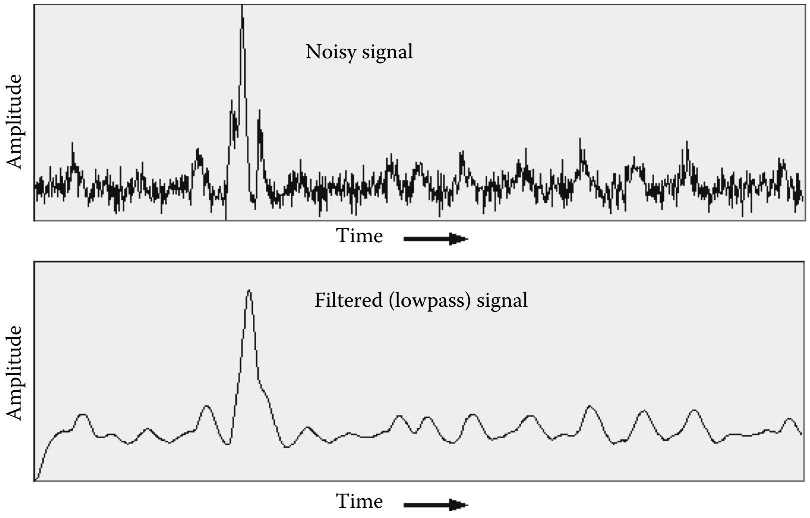

FIG. 19.15
Effect of low-pass filter on noisy signal.

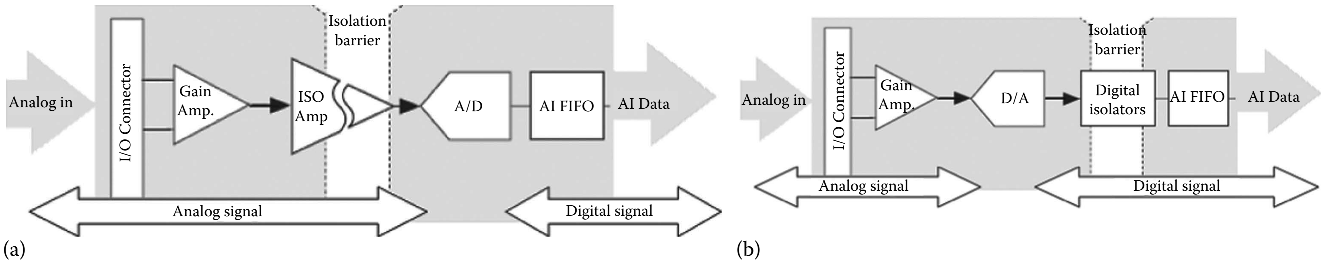

FIG. 19.16
Two approaches to isolate DAQ device. (a) analog isolation and (b) digital isolation.

primarily used for digital signals. A DAQ system that incorporates isolation can be implemented either with analog isolation in the signal-conditioning front end or with digital isolation on the digital data path. These two approaches are illustrated in Figure 19.16. New higher speed digital isolators based on MEMS (Micro Electromechanical Systems) technology have made the digital approach more feasible in recent years.

Sensor and Transducer Interfacing

Another important function of signal conditioning is providing the needed functions to interface a DAQ system to common sensors and transducers. The signal-conditioning requirements of some of the most common industrial sensors are listed in Table 19.2. We will look at some sensors and the key signal-conditioning requirements.

TABLE 19.2
List of Common Industrial Sensors and Their Signal-Conditioning Requirements

Sensor	*Signal-Conditioning Requirements*
Thermocouples	Cold-junction sensing and compensation, signal amplification
RTDs	Precision current source (excitation), lead-wire resistance compensation (three-wire and four-wire connections)
Strain gages	Wheatstone bridge completion, precision voltage or current source (excitation), signal amplification, offset nulling, shunt calibration
Load cells	Precision voltage or current source (excitation), signal amplification, offset nulling, shunt calibration

Thermocouples: The most common sensor used to measure temperature in DAQ applications is the thermocouple. The thermocouple is inexpensive and easy to use, does not require power or excitation, and can measure over a very wide range of temperatures.

The thermocouple consists of two wires of dissimilar metals. The junction of the two wires generates a small voltage, which varies with temperature. More specifically, the generated voltage is a function of the difference between this junction, called the *hot junction*, and the connection of the thermocouple wires to the measurement system, called the *cold junction*. In order to determine the absolute temperature of the hot junction, the signal conditioner or DAQ

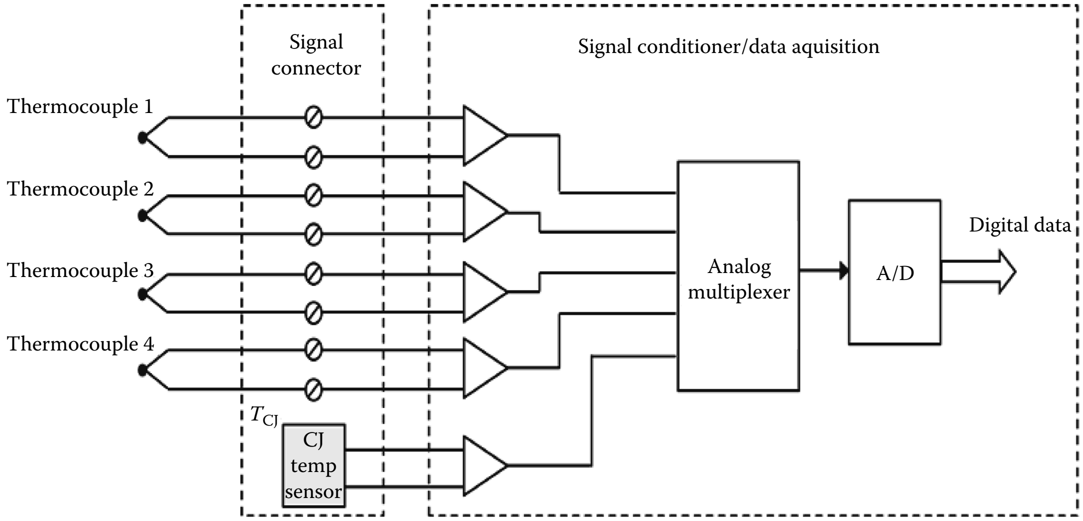

FIG. 19.17
Thermocouple instrumentation requires a cold junction sensor to measure the temperature of the cold junction, where the thermocouple wire connects to the measurement system.

system must also sense the temperature of the cold junction. DAQ systems designed for thermocouples often embed a single temperature sensor in the connector block to measure the cold junction (CJ) temperature as accurately as possible, as shown in Figure 19.17.

The ability of the cold junction temperature sensor to accurately sense the temperature at the actual connection of the thermocouple wire to the terminals has a direct impact of the overall measurement accuracy. Therefore, signal conditioner designers should design the signal connector block to be as isothermal as possible to minimize the thermal gradients that occur between the cold junction temperature sensor and any of the thermocouple wire terminals.

Resistance temperature detectors: Resistance temperature detectors (RTDs) are temperature sensors generally made from a pure metal whose resistance increases with increasing temperature. RTDs are popular for their stability, high precision, and highly linear operation. RTDs of different materials and resistance values are available, but the most common type is the platinum film PT100 sensor with a nominal resistance of 100 Ω at 0°C.

Because the RTD is a variable resistive device, signal conditioning must essentially adapt the DAQ system to measure the resistance of the RTD. The most common technique for this is to generate a constant current source and sense the resulting voltage drop across the RTD resistance. However, the lead wires connecting the signal conditioner to the RTD have some finite resistance, which, especially for longer runs of wire, can add significant errors to the measurement. Therefore, RTDs are commonly available with three-wire and four-wire configurations, which reduce or remove these errors with additional wires for sensing that do not carry the excitation current.

Strain gages and load cells: The strain gage is a very common device used in wide range of mechanical and structural measurements. The most common type is the bonded resistance foil strain gage whose electrical resistance, typically 120 or 350 Ω nominally, varies linearly with the strain applied to the device. Because the DAQ system must be able to effectively measure very small changes in resistance, strain gages are invariably used in a Wheatstone bridge circuit, shown in Figure 19.18. The Wheatstone bridge circuit consists of four resistive elements with a voltage excitation supply applied to the ends of the bridge. When the ratios R_1/R_2 and R_3/R_4 are equal, the bridge is said to be balanced, and the output V_0 is zero. V_0 will vary proportionally with changes in resistance to any resistor in the bridge.

Strain gages can occupy one, two, or four arms of the bridge, with any remaining positions filled with fixed value resistors. Half-bridge and full-bridge strain gage circuits are designed to increase the sensitivity by arranging the strain gage elements in opposing directions. Figure 19.19 shows signal-conditioning interfaces for quarter-bridge and full-bridge configurations. Note that the current carrying lead wires have a resistance R_L, which, if uncompensated, adds error to the measurement. Signal conditioners can minimize this error through three-wire connections (for quarter-bridge configurations), remote sensing of the excitation voltage, and

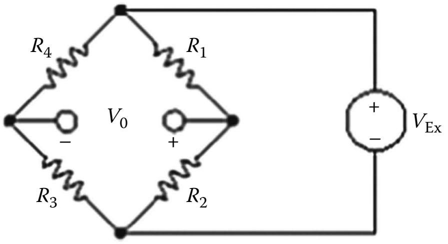

FIG. 19.18
Wheatstone bridge circuit used for strain gages and load cells.

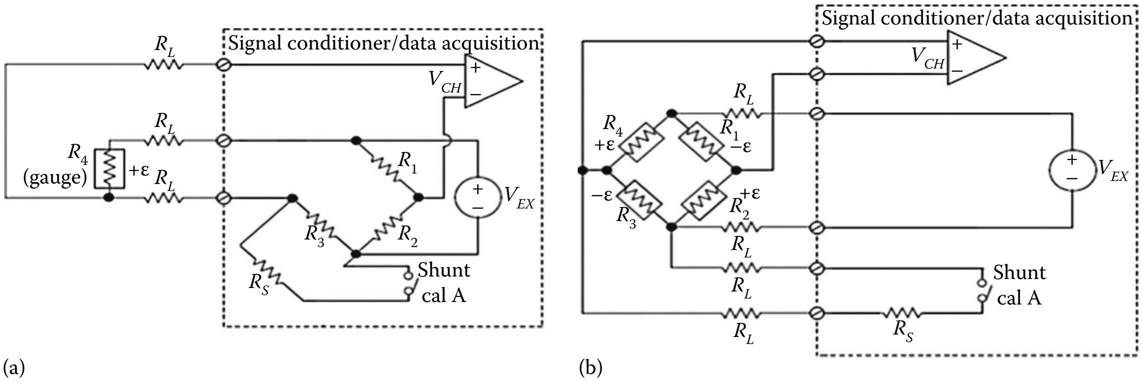

FIG. 19.19
Signal-conditioning circuitry for (a) quarter-bridge and (b) full-bridge strain gage configurations.

shunt calibration, which can be used to compensate for lead wire errors and other gain errors.

Load cells are simply engineered transducers that utilize strain gages bonded to a beam or mechanical component that deforms when force is applied. Interfacing a DAQ system to a strain-gage-based load cell is therefore equivalent to interfacing to a full-bridge strain gage. Similarly, some torque sensors and pressure sensors are also based on strain gage technology.

CONCLUSIONS

This chapter has introduced the fundamental components of DAQ systems, including A/Ds and D/As, multichannel architectures, system timing, signal conditioning, driver software, and application software. DAQ products come in all shapes and sizes, from very inexpensive and simple single-function devices to high-end sophisticated measurement systems that have been engineered to deliver top-notch performance, flexibility, and reliability in a wide range of environmental conditions. These high performance systems may incorporate advanced functions and features not discussed in this article. However, the basic concepts covered here are generally universal in the world of DAQ and form the foundation for even the more sophisticated DAQ systems.

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